FINAL REPORT

CONFERENCE ON CAPACITY AND WAKE VORTICES

Imperial College
London SW7 2BX

11 to 14 September 2001

Contracts N68171-00-M-6626 and F61775-01-WF009
with the USARDSG-UK and EOARD respectively

Purpose

The proposal which led to the Conference was submitted to the Army and AirForce Offices in London on 5 June 2000 and led to the above two contracts. It made clear the importance of Airport Capacity with continuing increase in the number of passengers, the consequent pressures placed upon Air Traffic Control, the limitations imposed by vortices shed from lifting bodies and the need for separation of landing aircraft. It was agreed that a Conference be arranged to allow an assessment of the problem today and of the likely situation in 2020 and to include presentations on capacity and wake vortices from fixed and moving wings. The emphasis was to be on vortices shed from wings and the rotating blades of rotorcraft.

The Conference was duly arranged as described in the Proposal, with a program formulated after consultation with colleagues within NASA, Ames and Langley Research Centers, the FAA, the US Army and AirForce and with corresponding agencies in Europe including the Civil Aviation Authority in the UK, the Deutche Luft und Raumfahrt in Germany, CERFACS and ONERA in France and representatives of Airbus and Boeing. The format was broadly as described in the proposal and the number of participants accorded closely with the requirement.

Program and attendees

A copy of the program is provided in the Appendix and shows that the Technical Program was divided into four parts, with the first three considered separately in the following sections and the results of the Discussion Session considered in the Concluding remarks. There were two sessions on Capacity and Strategies, six on Wake Vortices, three on Rotorcraft and one session to address the question 'Can we design for low drag, high lift and weak vortices' and with an extension to include the rotating blades of Rotorcraft. The technical program extended over three days with two hours each day on a concourse area to allow personal discussion over coffee and lunch, a short reception on the evening prior to the conference, and a dinner on the first evening.

Forty-four technical papers were presented, with nineteen from the United States and the remainder from Europe and divided as follows, one from Belgium, seven from France, nine from Germany, three from the Netherlands and five from the United Kingdom. Abstracts of each paper were provided in a booklet made available at the Conference and a copy is attached. The chairpersons of the thirteen sessions comprised five from the United States and the remainder Europeans with two from France, one from Germany, two from Italy, one from the Netherlands and two from the United Kingdom including the chairman of the Conference who chaired the Discussion Session. It should be noted that the DFS, FAA, and NATS were represented in the first two sessions with Chairmen from Airbus and Boeing, and that these two companies provided lead papers in the technical sessions. The various laboratories that provide supporting research were represented in the sessions on wake vortices, and the major contributors to the Rotorcraft sessions came from the US Army.

The total number of individuals who registered for the Conference was 101 and a list is attached. They came from the US (42, including 2 based temporarily in London), Belgium (1), France (10), Germany (18), Hong Kong (1), Italy (3), the Netherlands (4), South Africa (1), and the United Kingdom (21). These numbers are remarkable in view of the terrorist activity in New York and Washington on 11th September and related closure of airports and cancellation of flights to and from the US, but only four pre-registrants failed to arrive and only two of these from the US. It is also noteworthy that participants from all countries were greatly concerned by the loss of life, affects on their families and future travel arrangements. Nevertheless, the Conference proceeded without problems and probably helped to focus minds away from unfolding events in the US.

The Conference was made possible by financial support from NASA, the US AirForce and the US Army and with the considerable assistance of Dr Sam Sampath of the US Army Office in London. The technical program was formulated with advice from many of the presenters and the penultimate version was sent for comment to George Donohue, George Green, John Leverton, Klaus Huenecke, Eric Coustols, Thomas Gerz, Mike Harris, Philippe Spalart, Andy Kerr, Lyle Long, Charbel Rafoul and Sam Sampath. In addition, all Chairpersons were asked to contribute to this report and the unedited comments are also appendicised. The author of this report is grateful to all of the above, and to Serena Dalrymple, David Smith and Vim Patel of Imperial College and Joanne Paul of the Army Office, who assisted with Registration and in many other matters during the Conference. Staff of the Conference Office and of the Catering Department of Imperial College were also very helpful.

Capacity and strategies

Five of the papers in the two sessions were designed to set the scene for research on wake vortices and one to fulfil the same function for the later Rotorcraft sessions. In addition, a late paper on AVOSS was presented at the beginning of session 13 together with a statistical approach from the National Aerospace Laboratories in the Netherlands.

The paper by Donohue provided an excellent beginning with clear indications of safety requirements and their implications for aircraft movements. Three presentations characterised the problem of increased numbers of flights from the standpoints of a pilot and two major airports. Three others spelled out the approaches of the FAA, the Langley strategy of AVOSS and a statistical method proposed by the NLR. The general impression created by these papers was that improvements to Capacity could be obtained by reducing currently conservative separations between aircraft and that this could be managed without danger to allow increases in landing rates of the order of 15%. Further increases might be obtained by cones of acceptance at different parts of long runways for different categories of aircraft. It was clear that ground control also had a part to play with greater emphasis on timely clearing of stands and parking locations. It is unlikely that all requirements imposed by the increasing requirements can be met without additional runways and some attempt to move from the present hub and spoke arrangements of the US. In this respect, Runway Independent Aircraft have a role to play provided they can come and go without approaching vortices shed from fixed-wing aircraft or, alternatively, with proof that they can withstand the consequences.

It was made clear that there is a need to predict the locations of wake vortices up to 200 miles before landing and of the influence of atmospheric conditions for the remainder of the flight. Justification for reducing current separations has been provided by the AVOSS examination of 2300 landings at Dallas Fort Worth for which the vast majority could have been achieved with shorter separations. Also, tests at Frankfurt suggest that a combined high and low approach system has merit with long runways.

The final paper in session 2 raised the possibility of combinations of fixed-wing aircraft and rotorcraft so that the needs of smaller communities and airports might be met by a feeder system that transported passengers to major airports without the need for runways or taxi space. It is possible that the flight paths of the rotorcraft might be separate from those of fixed-wing aircraft so that their impingement upon Air Traffic Control would be distinct and more readily dealt with. Small jet-powered air taxis may also have a role to play but only away from major airports.

The Remote Sensing presentations of session 5 may be considered as part of Strategies in that they offer the possibility of determining the presence and strength of wake vortices and supplying the information to controllers, or to their adjunct computer programs. It is evident that problems of signal to noise ratio remain and that the location of the vortex can be elusive. Further work is necessary to remove these and other problems before reliable hands-off measurements can be obtained. Techniques of this type may have more immediate applications, for example in the control of parallel runways where the separation might otherwise preclude two aircraft landing at the same time but the ability to measure early on the glide path, rather than at the start of a runway, remains to be developed. The removal of this obstacle could allow experiments to resolve uncertainties associated with Reynolds-number effects and the importance of atmospheric conditions including limitations imposed on the utilisation of LIDAR by fog, rain and other adverse weather.

It seems unlikely that new ideas will come to fruition rapidly and that new runways and landing methods will be available in the near future. Comprehensive coverage by GPS will take some years to achieve, even in the continental US, and may not provide sufficient added information to increase landing rates. Equally, improved strategies for ground control may provide only small gains with the limitations imposed by existing airport configurations and the delays caused by ground handling, passengers and security, which is likely to pose a greater program as it is strengthened to counteract future terrorist attacks. Longer runways could help to improve the situation together with more runways that meet separation regulations but must be measured against environmental considerations, and legislation may prevent this approach for some years and perhaps permanently in some cases. This rather gloomy scenario suggests that all sources of improvement should be developed as fast as possible, with the immediate possibility of a 15% gain in landing rates by increased separations and perhaps double this figure with some control of vortices but over a longer time scale, and with greater gains by careful selection of locations for new runways, their construction and imaginative use.

Wake-vortex research

There were two main types of experimental contribution, one to characterise vortices in wind tunnels and the other to the development of passive and active control systems. The first raises the question of Reynolds number scaling and the ability to extrapolate to different wing configurations, and the second the possibility that designers and manufacturers will allow control systems to operate in flight. Neither question was resolved at the Conference but the first seems unlikely to be perfect and the second is doubtful at least in the immediate future. The Discussion section provided useful comments and these are addressed in the Concluding remarks.

The Airbus team has gone to considerable lengths to measure the strength of the vortices shed by their family of wings and the results are impressive, extensive and systematic. They made use of the DNW Tunnel with high costs and were supported by the DLR who developed their PIV system for operation in this comparatively large production tunnel. Simpler measurement methods were also employed and the research supported by experiments in water tunnels and with catapults. Extrapolation to flight presents the expected uncertainties, even though the wind-tunnel Reynolds numbers were high and the downstream extent of the flow is necessarily less than in practice, and extrapolation from one wing to another remains uncertain. The European Wake Vortex research is supported by the European Union, and has brought together these activities with others in France, and the LIDAR studies at the DLR and QinetiQ. The French efforts are further from engineering practice with examination of ways in which to influence the main wing-tip vortices by combinations of analysis, numerical methods and low-Reynolds number experiments involving interaction of imposed vortical flows with the naturally occurring vortices. There were hints of research with active control but no details were given. The results of the experiments show, for example that the vortices from a horizontal tail had no effect of wing and flap vortices, that the main landing gear reduced the rolling moment on following aircraft, and that a wing device helped to diffuse flap and tip vortices. In addition, the DLR reported a patent application to make use of counter-rotating vortices from a horizontal tail, the inboard edge of flaps, the wing-body junction and other devices so as to cause early

breakdown of wing-tip vortices and based on the so-called Rayleigh-Ludweig instability. There is a clear pattern to the research.

The Boeing approach is well known and involves active control of imposed low-frequency oscillation of ailerons or spoilers and flaps to weaken the wing-tip vortices so that their extent is reduced by nearly half. The arrangement seems practical in view of the low-frequency requirements of the imposed oscillations and the short time over which they are required but it seems unlikely that it will be retrofitted to existing aircraft.

In contrast to the support offered to Airbus by Government Laboratories in four countries and by three Universities, the support to Boeing came in the form of private contractors and one University and was on a much smaller scale. Also, the European effort was coordinated and financially supported by the European Union whereas there appeared to be no coordination of the US support and little expenditure.

The calculation efforts also addressed two facets of the problem, the trajectory and strength of vortices and possible methods for break up. The justification for the first is the possibility that the results may be used in conjunction with remote sensing and landing strategies to decrease the distance between consecutive aircraft and of the second that more acceptable active-control mechanisms may be invented. There were also attempts to provide more detailed understanding of the nature of the vortices and their stability characteristics. Doubts about the effects of numerical dissipation remain although efforts have been made to control them in combinations of Euler, RANS and LES codes.

Rotorcraft research

Two sessions were devoted to experiments with rotorcraft and one to calculations. The experiments were performed at the DLR in Gottingen and by the US Army (AMCM-RDEC) and colleagues at NASA, Ames Research Center with two additional contributions, one each from the Universities of Glasgow and Maryland. The calculations stemmed from the Pennsylvania State University, AMCM-RDEC and a US contractor.

The experiments at Gottingen involved helicopters and combinations of visualisation methods and PIV. The emphasis remains on the application of instrumentation but it is evident that the program will be able to move to some characterisation of fully scale vortex interactions. No company involvement was reported. Two Universities examined the trailing vortex wake from a rotor and interactions between main and tip vortices with small-scale experiments and a range of instrumentation, and the Ames Research Center made use of its NFAC facility to assess methods of modifying the tip vortex. A presentation by Boeing made clear their interest in airport operation involving rotorcraft and the need to overcome the potential problem of interaction with wakes from fixed-wing aircraft. The effort reported from AMCM-RDEC/Ames may require changes in view of the urgent need for consideration of runway independent aircraft in the US and the availability of the unique capabilities of the NFAC. There were promising concepts such as easily deployed leading edge vortex generators to weaken the tip vortex and reduce noise at critical times.

The calculations, all from the US, were technically proficient. Two were concerned with numerical methods, that from the Pennsylvania State University addressed the future use of virtual reality rather than details of rotorcraft, and that from AMCM-RDEC overset grids and their application to near-rotor wakes. One of the remaining two presentations was concerned with commercial codes and the second, an AMCM-RDEC contribution, emphasised the need for careful use of a suite of codes, supported closely by measurements, and with the NFAC as an essential facility.

In general, the three sessions presented interesting papers and the impression that the US effort requires some coordinated changes if the concept of runway independent aircraft is to be realised. In particular, the availability of the NFAC offers the possibility of full-scale experiments and, though expensive to operate, provides a basis for solution of problems that cannot be solved in other ways.

Concluding remarks

It seems doubtful that any of the methods or results presented at this conference will allow large and immediate improvement in the control of aircraft in flight or in numbers allowed to land per unit time. On the other hand, a 15% increase in landing rates may be achieved now and with substantial increase in passengers carried and related revenue. This conclusion is well supported by AVOSS tests carried out at DFW airport. The papers presented in the sections on Capacity and Strategies suggest that additional gains will require more concrete to be poured at large airports, supported by aircraft with GPS systems as proposed by NASA and with Runway Independent Aircraft to reduce the number of new runways which would otherwise be required. Greater use of long-haul flights to and from medium-sized cities will also help and, in particular, can dilute the need for the present hubs with current density of short-haul feeder aircraft.

The larger gains require longer-term contributions to a problem that exists today in many airports and can only get worse with a possible doubling of air traffic by 2020. It appears, however, that some major airports can manage for some time and, for example, there are no plans to decrease separations at Heathrow. Some airports have adequate facilities under good weather conditions but defects such as close proximity of parallel runways require that one be closed when atmospheric conditions deteriorate. The San Francisco International Airport is an excellent example and it is possible that on-line sensing of vortices by LIDAR may help to overcome this problem to some extent, but considerable improvements to present systems are required and cannot be expected in the near term. Tests conducted so far at SFO and DFW seem to have been in fair weather and the limitations in poor weather need to be explored.

More accurate information of wake vortices is likely to allow improvements in landing procedures and separations, and is likely to provide a further gain in landing rates of around 15%. Thus, there is a continuing need for research that will provide information of different configurations and for the development of calculation methods that will allow, at best, the *a priori* determination of the effects of changes in wing shape, angle of attack and attitude on lift, drag and vortex strength and, at worst, the ability to interpolate between tests conducted with known configurations and to extrapolate to new configurations with known confidence intervals. It was evident from the presentations and the Discussion that dependable *a priori* calculations are not possible at the moment but the basic ingredients are available and, with close cooperation between calculation developments and measurements, the lesser requirement can be met and with improving accuracy as the research continues to focus.

There is a need to compare results obtained at low Reynolds numbers with those in large wind tunnels and subsequently with flight, with decreasing detail of experimentation as scale is increased. Though not evident at the Conference, this may happen within companies as, for example, with the Boeing active-control system referred to below. In this way, a basis for extrapolation to different wings may be possible and the ideas stemming from experiments in small and flexible configurations may be evaluated. Detailed quantification of the Reynolds-number effect is likely to require remote and on-line measurements of the size and strength of vortices and this, in turn, requires improvements to present measurement methods. A solution to this problem would also allow resolution of the effects of atmospheric conditions on vortex dissipation and break-up and allow the FAA to bring together computer-based method for the representation of aircraft locations and their wakes together with atmospheric predictions. It is interesting that no results of wing performance in production wind tunnels were reported from the US.

The emphasis on control of vortices in the papers of the Conference is welcome and necessary. There were many suggestions for passive control and occasional reference to active control with Boeing describing their practical system. The passive control arrangements concentrated on providing secondary vortices to mix with the primary vortices with subsequent breakdown over a distance smaller than would otherwise occur, and it appears the reliance on the Crow instability is unlikely to result in acceptably short break-up distances. The DLR passive-control approach of mixing vortices from several sources may have promise in the medium field. Active control can involve comparatively simple devices to generate secondary vortices and they may require deployment for limited and selected times, but none described at the conference is

likely to be operational for some time. The Boeing approach, which makes use of low-frequency imposed oscillations, could be deployed now with consequent separation reductions of some 40% but it is unlikely to be used on current aircraft since it involves changes to landing operations and the provision of added mechanisms and a control system. This is regrettable since it appears comparatively economical to build and evaluate.

The different approaches of the European and US organisations was very clear with closely coordinated programs in the former and supported financially by the European Union, and uncoordinated programs in the US and supported by a number of Government Agencies. Coordination does not always ensure good research and a practical outcome but uncoordinated research can preclude it.

APPENDICES
Conference program
List of attendees
Comments from Chairpersons
Booklet of abstracts

Conference on Capacity and Wake Vortices
Imperial College
London SW7 2BX
11 to 14 September 2001

TUESDAY 11 SEPTEMBER

17.30 to 1930	**Reception and Registration on the Concourse**	

WEDNESDAY 12 SEPTEMBER

08.15	**Registration on the Concourse**	
09.00	**Introductory remarks in Lecture Theatre 220**	
	SESSION 1 CAPACITY AND STRATEGIES, 1	
	Chairman	**Chester Ekstrand, Boeing**
09.10	**George Donohue, G Mason University**	Wake vortices and capacity constraints
09.50	**Stefan Wolf, IFALPA**	A pilot's view of capacity and safety
10.20	**Neil May, NATS**	Separations at Heathrow
11.00	**COFFEE**	
	SESSION 2 CAPACITY AND STRATEGIES, 2	
	Chairman	**Marc Maurel, Airbus**
11.30	**George Greene, FAA**	FAA's research strategy
12.00	**Jens Konopka, DFS**	Wake-vortex environment at Frankfurt
12.30	**John Leverton, AHS**	Improving airport capacity using vertical flight
13.00	**LUNCH**	
	SESSION 3 EXPERIMENTS WITH WAKE VORTICES, 1	
	Chairman	**Anton De Bruin, NLR**
14.00	**Klaus Huenecke, Airbus**	Recent developments in industrial wake vortex research
15.00	**Don Delisi, NWRI**	Vortex evolution and characterisation
15.30	**Leo Veldhuis, TU Delft**	PIV measurements behind an A340 model in a tow tank.
16.00	**COFFEE**	
	SESSION 4 CALCULATIONS OF WAKE VORTICES, 1	
	Chairman	**Alan Bilanin, Continuum Dynamics**
16.30	**Thomas Gerz, DLR**	Wake vortex prediction and observation in the atmosphere
17.00	**Fred Proctor, LaRC**	Wake vortex transport and decay with parallel runways.
17.20	**Bob Robins, NWRA**	Simulations of vortex evolution
17.40	**Florent Laporte, CERFACS**	Simulations of large aircraft type wakes
19.30	**DINNER IN THE SENIOR COMMON ROOM**	

THURSDAY 13 SEPTEMBER

	SESSION 5	**REMOTE SENSING**	
	Chairman	**Skip Fletcher, Ames Research Center**	
09.00	**Mike Harris, QinetiQ**		Field-trial measurements of wakes with laser radar
09.30	**Steve Hannon, CTI**		Detection and tracking of wake vortices within approach and departure corridors
09.50	**Friedrich Koepp, DLR**		Long-range detection of aircraft wake vortices
10.20	**Rick Heinrichs, MIT**		Wake vortex measurements of the V-22 and XV-15 tiltrotor aircraft with a CW coherent laser radar
11.00	**COFFEE**		
	SESSION 6	**CALCULATIONS OF WAKE VORTICES, 2**	
	Chairman	**Ulrich Schumann, DLR**	
11.25	**Florent Laporte, CERFACS**		Instabilities of wake-vortex models in the near and far fields
11.55	**Jeffrey Crouch, Boeing**		Forcing the breakup of trailing vortices
12.20	**Henri Moet, CERFACS**		The effect of atmospheric turbulence on wake vortices
12.45	**Greg Winkelmans, U de Louvin**		Prediction of trajectories and decay of wake vortices
13.10	**LUNCH**		
	SESSSION 7	**EXPERIMENTS WITH WAKE VORTICES, 2**	
	Chairman	**Michael Vaughan, DERA**	
14.10	**Philippe Spalart, Boeing**		Can we reduce the wake-vortex hazard by modifying the wing'
14.50	**Omer Savas, UCB**		Wake alleviation by vortex control
15.10	**Peter Bearman, IC**		Experiments on wake vortex control
15.30	**Patricia Coton, ONERA**		A new facility to study near to far vortex fields
15.50	**COFFEE**		
	SESSION 8	**ROTORCRAFT EXPERIMENTS, 1**	
	Chairman	**Andy Kerr, US Army**	
16.20	**Gerd Meier, DLR**		Helicopters and vortices
17.05	**Leo Dadone, Boeing**		Rotorcraft wakes in the context of airport operations
17.30	**Gerd Meier, DLR**		Background Oriented Schlieren

FRIDAY 14 SEPTEMBER

	SESSION 9	**ROTORCRAFT CALCULATIONS**	
	Chairman	**Marco Borri Politecnico Milano**	
09.00	**Lyle Long, PSU**		Recent advances in computing and visualisation
09.35	**Frank Caradonna, AMRDEC**		Advances in rotorcraft wake aerodynamics
10.00	**Roger Strawn, AMRDEC**		Overset-grid models for rotors and wakes
10.25	**Alex Boschitsch, Continuum Dyn**		Aircraft and rotor wakes
11.00	**COFFEE**		
	SESSION 10	**EXPERIMENTS WITH WAKE VORTICES, 3**	
	Chairman	**James Hallock, Volpe**	
11.30	**Alex Corjon, Airbus**		Towards wake alleviation for transport aircraft
12.00	**Will Graham, U Cambridge**		Merger of co-rotating vortex pairs
12.20	**Thomas Leweke, U Marseilles**		Experiments with short-wave instabilities on vortex pairs.
12.40	**Roland Stuff, DRL**		The role of PIV in the design of transport aircraft for breakdown of trailing vortices
13.00	**LUNCH**		
	SESSION 11	**ROTORCRAFT EXPERIMENTS, 2**	
	Chairman	**Piergiovanni Renzoni, CIRA**	
14.00	**Gordon Leishman, U Maryland**		The trailingvortex wake from a helicopter rotor
14.30	**Roddy Galbraith, UGlasgow**		Detail of main/tail rotor vortex interaction
14.50	**Ken McAlister, ARC**		Altering the tip vortex or a rotor
15.10	**Markus Raffel, DLR**		PIV measurements of wake vortices
	SESSION 12	**CALCULATIONS OF WAKE VORTICES, 3**	
	Chairman	**Alex Corjon, Airbus**	
15.30	**Laurent Jacquin, ONERA**		Stability properties and unsteadiness of wake vortices
15.50	**Abraham Elsenaar, NLR**		Optimisation of the upper limit of the rolling moment by a vortex pair
	SESSION 13	**DISCUSSION**	
	Chairman	**Jim Whitelaw Imperial College**	
	Two papers on Capacity and strategies:		
16.20	**David Rutishauser, LaRC**		AVOSS: overview and future direction
16.35	**Anton de Bruin, NLR**		Aspects of wake-vortex safety with a probabilistic approach
16.50	**Discussion Topics**		Can we design for low drag, high lift and weak vortices? Can we design rotors to minimize adverse blade-vortex interactions without reduction in performance?
18.00	**CLOSE**		

Conference on Capacity and Wake Vortices

London, 11 - 14 September 2001

Registrants

	Surname	Initials	Organisation	Email
1	Agnew	Dr Paul	Met Office	paul.agnew@metoffice.com
2	Al-mahadin	Mr Aziz	University of Hertfordshire	almahadin@yahoo.com
3	Bauer	Dipl.-Ing. Tobias	IFGC, TU Braunschweig	t.bauer@tu-bs.de
4	Bearman	Professor Peter	Aero Dept, Imperial College	p.bearman@ic.ac.uk
5	Bilanin	Alan	Continuum Dynamics Inc	alan@continuum-dynamics.com
6	Borri	Professor Marco	DIA, Politecnico di Milano	marco.borri@polimi.it
7	Brown	Dr Richard	Aero Dept, Imperial College	r.e.brown@ic.ac.uk
8	Bruin	Ir Anton de Bruin	NLR	bruina@nlr.nl
9	Bryant	Mr Wayne	NASA Langley Research Center	w.h.bryant@larc.nasa.gov
10	Caradonna	Dr Francis	Army Aeroflightdynamics Directorate	fcaradonna@mail.arc.nasa.gov
11	Corjon	Alexandre	EADS Airbus SA	alexandre.corjon@airbus.aeromatra.com
12	Coton	Patricia	ONERA Lille	coton@imf-lille.fr
13	Cromarty	Mr Peter	Civil Aviation Authority UK	peter.cromarty@srg.caa.co.uk
14	Crouch	Dr Jeffrey	The Boeing Company	jeffrey.d.crouch@boeing.com
15	Dadone	Leo	The Boeing Company	leo.dadone@PHL.boeing.com
16	Dafa'Alla	Dr Adil A	Airbus UK	adil.dafaalla@baesystems.com
17	Dasey	Timothy	MIT Lincoln Laboratory	timd@11.mit.edu
18	Delisi	Dr Donald	North West Research Assoc Inc	don@nwra.com
19	Denton	Mr T S A	CSIR Defencetek	tdenton@csir.co.za
20	Donohue	Dr George L	George Mason Univ	gdonohue@gmu.edu
21	Durston	Donald	NASA Ames Research Center	ddurston@mail.arc.nasa.gov
22	Ekstrand	Chester	Boeing Commercial Airplanes	chester.l.ekstrand@boeing.com
23	Elphick	Mr Gerald	Airbus UK	gerry.elphick@baesystems.com
24	Elsenaar	Abraham	National Aerospace Laboratory NLR	elsenaar@nlr.nl
25	Fares	Dipl-Ing Ehab	Aerodynamisches Institut der RWTH-Aachen	ehab@aia.rwth-aachen.de
26	Fiduccia	Mr Paul	Aviation Systems Engineering, Inc	pfiduccia@aol.com
27	Fletcher	Dr Skip	NASA Ames Research Center	sfletcher@mail.arc.nasa.gov
28	Galbraith	Professor Roderick	Aero Dept, University of Glasgow	r.a.m.galbraith@aero.gla.ac.uk
29	Gerz	Thomas	DLR Oberpfaffenhofen	thomas.gerz@dlr.de
30	Graham	Dr Will	Engineering Dept, University of Cambridge	wrg@eng.cam.ac.uk
31	Greene	Mr George	Federal Aviation Administraton	g.c.greene@larc.nasa.gov
32	Hallock	James	Volpe National Transportation Systems Center	hallock@volpe.dot.gov
33	Hannon	Stephen M	CTI	steveh@ctilidar.com
34	Harris	Dr Michael	Qinetic	mharris@qinetiq.com
35	Haverkamp	Sven	ILR, TU-Aachen	haverkamp@ilr.rwth-aachen.de
36	Heinrichs	R M	MIT	heinrichs@ll.mit.edu
37	Heyes	Dr Andy	Mech Eng Dept, Imperial College	a.heyes@ic.ac.uk
38	Hoad	Miss Deborah	Met Office	debi.hoad@metoffice.com
39	Hogan	Ms Christine	Aero Dept, Imperial College	c.hogan@ic.ac.uk
40	Hubbard	Mr Simon	Mech Eng Dept, Imperial College	simon.hubbard@ic.ac.uk
41	Huenecke	Klaus	Airbus Dasa	k.huenecke@airbus.dasa.de
42	Huenecke	Caren	Airbus Dasa	c.huenecke@airbus.dasa.de
43	Jacquin	Laurent	ONERA	jacquin@onera.fr
44	Kerr	Mr Andrew	US Army Aeroflightdynamics Directorate	akerr@mail.arc.nasa.gov

45	Koepp	Mr Friedrich	DLR Oberpfaffenhofen	friedrich.koepp@dlr.de
46	Konopka	Dr Jens	Deutsche Flugsicherung GmbH	jens.konopka@dfs.de
47	Kroeger	Captain Uwe	IFALPA, Vereinigung Cockpit e.v.	office@vcockpit.de
48	Laporte	Florent	CERFACS	flaporte@cerfacs.fr
49	Leishman	Professor Gordon	Aerospace Eng, University of Maryland	leishman@eng.umd.edu
50	Leverton	Dr John	AHS International	leverton@erols.com
51	Leweke	Dr Thomas	IRPHE/CNRS	leweke@irphe.univ-mrs.fr
52	Long	Professor Lyle	Penn State University	lnl@psu.edu
53	Luckner	Dr Robert	Airbus Dasa	robert.luckner@airbus.dasa.de
54	Lynn	Mr Richard	QinetiQ	rlynn@qinetiq.com
55	Marren	Katherine	National Air Traffic Services Ltd	katherine.marren@nats.co.uk
56	Maurel	Marc	EADS Airbus SA	marc.maurel@sirbus.aeromatra.com
57	May	Mr Neil	National Air Traffic Services Ltd	neil.may@nats.co.uk
58	McAlister	Dr Kenneth	Aeroflightdynamics Directorate	kmcaslister@mail.arc.nasa.gov
59	McCluer	Megan S	NASA Ames Research Center	mmccluer@mail.arc.nasa.gov
60	Meier	Dr Gerd E A	DLR, Goettingen	g.e.a.meier@dlr.de
61	Miller	Dr Nelson	Federal Aviation Administration	nelson.miller@tc.faa.gov
62	Moet	Henri	CERFACS	moet@cerfacs.fr
63	Nene	Dr Vilas	Mitre Corp	vnene@mitre.org
64	Nicolaon	Jean-Pierre	Eurocontrol	jean-pierre.nicolaon@eurocontrol.fr
65	Pansky	Mr Steve	Federal Aviation Administration	steve.pansky@faa.gov
66	Passman	Mr Robert	Federal Aviation Administration	robert.passman@faa.gov
67	Preatoni	Gaetano	Agusta	aer@agusta.it
68	Proctor	Dr Fred	NASA Langley Research Center	f.h.proctor@larc.nasa.gov
69	Raffel	Dr Markus	DLR, Goettingen	markus.raffel@dlr.de
70	Ramadan	Dr Ashraf	City University London	a.ramadan@city.ac.uk
71	Reichenbach	Dr Roy	NASA Ames Research Center	roy.reichenbach@faa.gov
72	Renzoni	Piergiovanni	CIRA	p.renzoni@cira.it
73	Robins	Mr Robert	North West Research Assoc, Inc	bob@nwra.com
74	Robinson	Mr Jerry	The Boeing Company	jerry.j.robinson@boeing.com
75	Rutishauser	Mr David	NASA Langley Research Center	d.k.rutishauser@larc.nasa.gov
76	Sampath	Dr Sam	US Army	ssampath@usardsguk.army.mil
77	Savas	Professor Omer	University of California Berkeley	savas@me.berkeley.edu
78	Schroder	Professor Wolfgang	Aerodynamisches Institut der RWTH-Aachen	office@aia.rwth-aachen.de
79	Schumann	Ulrich	DLR Oberpfaffenhofen	ulrich.schumann@dlr.de
80	Skiple	Scott	US ARMy	sskiple@usardsguk.army.mil
81	Smith	David	Mech Eng Dept, Imperial College	d.smith4@ic.ac.uk
82	Spalart	Philippe R	The Boeing Company	prs6794@deer.cfd.ca.boeing.com
83	Stilp	Dr Thilo	Airbus Toulouse	thilo.stilp@airbus.fr
84	Strawn	Dr Roger	US Army Aeroflightdynamics Directorate	rstrawn@mail.arc.nasa.gov
85	Stuff	Roland	DLR	roland.stuff@dlr.de
86	Stumpf	Eike	DLR German Aerospace Center	eike.stumpf@dlr.de
87	Tittsworth	Jeffrey	Mitre Corp	allen@mitre.corp
88	Tong	Dr Kwok-On	Boeing Air Traffic Management	kwok-on.tong@boeing.com
89	Tung	Dr Chee	US Army Aeroflightdynamics Directorate	tung@merlin.arc.nasa.gov
90	Vasatka	James	The Boeing Company	james.e.vasatke@boeing.com
91	Vaughan	Michael	DERA	michael@gladeantiques.com
92	Veldhuis	Leo L M	TU Delft	l.l.m.veldhuis@lr.tudelft.nl
93	Vidal	Antoine	EuroControl	antoine.vidal@eurocontrol.fr
94	Vollmers	Visa	DLR Gottingen	heinrich.vollmers@dlr.de
95	Whitehouse	Mr Glen	Aero Dept, Imperial College	g.whitehouse@ic.ac.uk

96	Whitelaw	Professor J H	Mech Eng Dept, Imperial College	j.whitelaw@ic.ac.uk
97	Winckelmans	Professor Gregoire	Universite Catholique de Louvain	gsw@term.ucl.ac.be
98	Winkler	Dr Sean	MIT Lincoln Laboratory	sean@ll.mit.edu
99	Wolf	First Officer Stefan	IFALPA, Vereinigung Cockpit e.v.	wolf@t-online.de
100	Wulleswinkel	Heuk	WAC	h.n.wulleswinkel@planet.nl
101	Zhou	Yu	Hong Kong Polytechnic University	mmyzhou@polyu.edu.hk
	13-Sep-01			

COMMENTS FROM CHAIRMEN

Remote sensing of wake vortices

Dr Skip Fletcher
Director of Aerospace
NASA, Ames Research Center

With the continuing increase in the demand for safe and efficient air travel, and the problems related to congestion of airport runways, delaying landings and takeoffs, there is a growing concern about the impact of the congestion and delays on air traffic safety. Suggestions have been made to decrease the separation time between landings, as well as between takeoffs, as a way to increasing the capacity of airports. The presence of wake vortices that occur following each landing, and takeoff, pose a potential safety problem, depending upon the strength of the vortices, as well as the associated environmental turbulence conditions. As a consequence, there is a significant need to identify and measure the characteristics of each vortex system, as well as develop appropriate models for predicting these systems as a key to achieving the necessary safe capacity growth.

While various techniques have been proposed for the measurement of these vortex systems, the coherent laser radar (lidar) system is emerging as the primary technique that may be used for the detection and evaluation of full-scale aircraft wake vortices. Short-range conditions may be measured with continuous wave (CW) lidar systems, whereas longer-range conditions may be measured with a pulsed Doppler lidar system. Progress has been made in refining the instrumentation and facilities for wake vortex detection and evaluation, and the accuracy of these systems is improving. Nevertheless, the improvement in airport capacity resulting from decreased aircraft spacing times will not occur until there is a uniform procedure for detecting and evaluating the characteristics of wake vortices, as well as the availability of a reliable measurement technique.

Significant advancements have been made in the development of real time autonomous pulsed Doppler lidar systems, however reliability and maintainability continue to be an area warranting attention. These pulsed systems provide an opportunity to evaluate vortices at a longer stand off range, however the interaction of winds, wind shear, local turbulence, and other weather conditions have not been resolved.

A number of issues associated with the remote sensing of wake vortices have been made, and many of these issues warrant further investigation in order to continue progress toward increased airport capacity.

- How accurately can wake vortices be distinguished from surrounding turbulence levels?
- What is the reliability, repeatability, and uncertainty of wake vortex circulation values?
- What is the error resulting from the time difference between scans of the vortex system?
- What is the impact of fog and humidity on the measurement of wake vortices?
- When comparisons are made between wind tunnel data and full-scale flight, what corrections are made for the undercarriage and the temperature differences?
- Could airborne pulsed Doppler lidar be used in conjunction with ground-based pulsed Doppler lidar to provide a three-dimensional image of the vortex?
- Is triangulation of remote sensing lidar systems viable or warranted?
- What weather conditions cause wake vortices to move up rather than down?

Impressions from the Conference on Airport Capacity and Wake Vortices.

A.C. de Bruin (NLR)

General impressions

The topic of the conference was well received as indicated by the large participation with over 60 participants from Europe and about 40 participants from the US. The conference was well organised and the presentations were in general of high quality. Unfortunately, some participants could not travel to the conference due to the dramatic events in New York and Washington that occurred the day before the meeting.

Airport capacity

Airport capacity in relation to wake vortex separation distances was directly touched in only a few presentations. The interesting presentation by Donohue was most directly related to this subject. New airport operational procedures for improved airport capacity were presented by Konopka (DFS). An interesting overview of the wake vortex safety monitoring at Heathrow was given by May (NATS). In a number of presentations (Leverton, AHS; Dadone, Boeing) it was argued that vertical rotorcraft and tilt-rotor aircraft could increase airport capacity. This may be true, provided that the environmental impact can be sufficiently minimised.

Aircraft wake physics

Most presentations were on improved understanding of wake physics. Detailed experiments in test facilities (mostly with PIV techniques supported by flow visualisations) or field tests with LIDAR were presented. These experiments yielded detailed results on wake vortex merging (Graham, U. of Cambridge) and the effect of wake instabilities on the evolution of the wake flow-field (Leweke, U. Marseille; Bearman, IC; Crouch, Boeing; Savas, UCB). Interesting experimental results on the interaction between co- or counter-rotating vortices were reported. A number of presentations dealt with tests in a water-tank (Veldhuis, TUD; Crouch, Boeing; Huenecke, Airbus-D; Delisi, NWRA), which allows to study the wake evolution up to the far-wake region. The new free-flying model test facility, as presented by Coton (ONERA), is an interesting alternative for the water tank tests.

Substantial progress was reported by Hannon (CTI) with their long-range wake tracking based on a pulsed LIDAR system. This system seems directly applicable in an operational wake vortex tracking and warning system.

For making detailed field tests the LIDAR triangulation method reported by Harris (QinetiQ) and Gerz (DLR) seems a very promising technique. An interesting statement about the size of vortex cores was made by Heinrichs (MIT). Under favourable weather conditions with high signal-to-noise ratio they reported peak cross-flow velocities as high as 45 m/s and vortex core sizes as small as .01b (whereas it is generally believed that these are in the order of .05b).

Interesting progress was reported in calculating the near wake and the extended and far wake region (e.g. presented by Laporte, CERFACS). To suppress numerical dissipation effects, adequate grids and high-order numerical schemes are necessary features. The steady increase in computer capacity enables to study systematically wake evolution and decay under various controlled atmospheric conditions (e.g. as presented by Moet, CERFACS; Proctor, LaRC). This work is important for calibrating simpler engineering type prediction methods that can be used in real-time wake prediction methods. Comparing the results of engineering prediction methods with field trial data (e.g. by Rob Robins, NWRA) also forms a basis for improving the simpler prediction methods, provided that the local atmospheric conditions are known.

Helicopter wake physics

Very interesting experimental results were reported on the evolution of helicopter and tilt-rotor wakes. Measurements with LIDAR show a gradual change from helicopter to normal fixed wing aircraft wakes during transition to forward flight (Heinrichs, MIT). Very detailed measurements of rotor-tip wake interactions were reported (Leishman, U. Maryland; Galbraith, U. Glasgow; McAllister, ARC; Meier, DLR). Numerical simulations of helicopter wakes were reported by Caradonna and Strawn (AMRDEC).

Aircraft design for wakes having low impact on following aircraft.
As shown in the presentations by Elsenaar (NLR) and Spalart (Boeing) altering the spanwise wing-loading will to some extend influence the cross-flow velocity distribution in the wake. This property can be used to reduce the impact of the wake on a following aircraft at the expense of a somewhat higher level of induced drag.

A second promising method to influence the wake characteristics is to exploit short and long-wave wake instability mechanisms that lead to an early break-up of the wake vortex system. This can be achieved either active (patented solution of Boeing, as presented by Crough) or passive (as presented by Huenecke, Leweke and Stuff). Much progress was reported in the understanding of the various instability mechanisms. So far tests were only made on laboratory scale. The active system proposed by Boeing has been demonstrated in water-tank tests. It seems that with such a system the time for wake break-up can be reduced significantly. The required separation distance would be less than 3 NM behind a heavy aircraft. Some potential practical problems (passenger comfort, wing fatique) still remain to be considered.
With regard to the passive approach it seems that there are at least three slightly different concepts tested in Europe. Limited experimental and theoretical evidence on these concepts was presented at the conference. Full scale proof of concept seems needed.
The wake after break-up is composed of ring vortices. Entering such a wake will lead to a dynamic (periodic) interaction. According to the experimental work of Delisi (NWRA) the decay of ring vortices is slower than of a comparable 2D wake. It also still needs to be proven that such a wake is less benign to a following aircraft than that of a normal pair of vortices.

Concluding remarks
Much excellent work has been presented at the conference, especially on how various instabilities in the wake can lead to rapid destruction of the wake. However no definite conclusions can be made with regard to the applicability to real aircraft. Also more work is needed to prove the safety benefits and to define safe (reduced) separations with such rapid wake destruction concepts.
Within Europe most of the work is done in the various EU co-sponsored projects (S-Wake, C-Wake, ATC-Wake and AWIATOR), within U.S. new projects are being initiated to come to an operational system for reduced separations for closely spaced parallel runways (as presented by Greene, FAA; Rutishauser, LaRC). For assessing overall levels of safety both in the US and Europe a probabilistic safety assessment methodology is being developed.